PERIODIC SHORELINE MORPHOLOGY, FIRE ISLAND, NEW YORK

Mark B. Gravens[1], AM. ASCE

Abstract: The presence of shoreline undulations along the Atlantic coast of Fire Island, NY requires careful consideration in developing erosion control and hurricane protection plans and design alternatives for the protection of the Fire Island barrier and the Long Island mainland. An analysis and geometric characterization of these morphologic shoreline features revealed that the magnitude of the shoreline undulations approximates typical protective berm design widths and exceeds typical advance nourishment beach widths. Because shoreline undulations are natural morphologic features of the Fire Island shoreline their presence after project construction must be anticipated. Conclusions drawn from the analysis of the Fire Island shoreline undulations indicate that the design berm width could be compromised well before scheduled renourishment if explicit consideration of shoreline undulations is not included in the development of the design cross-section.

INTRODUCTION

Fire Island is one of several barrier islands that lie along the southern edge of Long Island, New York. The Fire Island barrier is approximately 50 km in length and is bounded on the east by Moriches Inlet and on the west by Fire Island Inlet. North of the island lies Great South Bay and to the south is the Atlantic Ocean (Fig.1). The average net longshore sand transport rate on Fire Island is from east to west, and its magnitude is estimated at approximately 200,000 m^3/year with representative values for west- and east-directed transports of 350,000 and 150,000 m^3/year, respectively (Rosati et al. 1999). The Atlantic shoreline of Fire Island is consistently characterized by undulating shoreline features that are locally referred to as longshore sand waves or erosion waves. The shoreline features discussed in this paper are distinguished from commonly observed beach cusps in that the shoreline undulations found on Fire Island appear to be more random

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with respect to their spatial distribution and have wavelengths that are substantially longer than those of beach cusps. The shoreline features are referred to as shoreline undulations in this paper to distinguish them from migratory longshore sand waves that have been observed to maintain their identity through collective movement over a lifetime that can approach years (Sonu 1968, Thevenot and Kraus 1995). Because shoreline undulations are natural morphological features of the Fire Island shoreline, the design of any potential beach erosion control and hurricane protection project should anticipate that shoreline undulations will be present both during and after construction of the project. Therefore, it is important from a design perspective to quantify the physical characteristics of these naturally occurring morphological features.

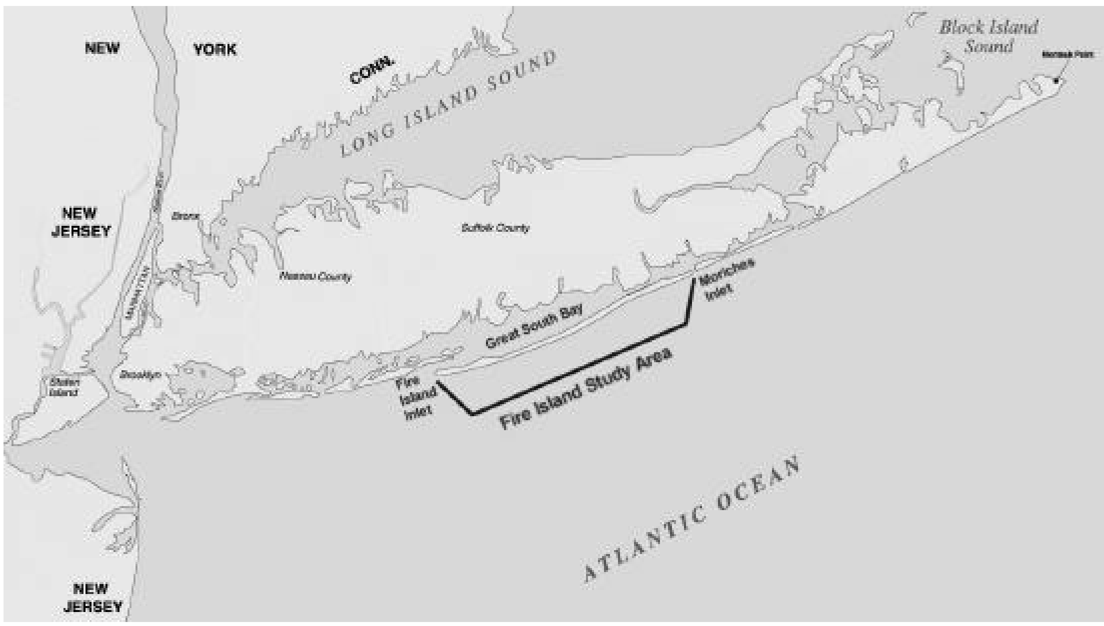

Fig. 1. Fire Island site map.

This paper will present the results of analyses undertaken to quantitatively characterize shoreline undulations observed and measured along the Fire Island shoreline. Although the temporal scale associated with individual shoreline undulations is short compared to the temporal scale of a shore protection project, the persistent presence of multiple shoreline undulations requires detailed attention at the longer temporal scale associated with the development of a comprehensive erosion control and hurricane protection plan. These analyses were conducted as one part of the "Coastal Processes Studies for the South Shore of Long Island, Fire Island to Montauk Point (FIMP)," by the U.S. Army Engineer Waterways Experiment Station (WES) in support of the "Beach Erosion Control and Hurricane Protection Project Fire Island Inlet to Montauk Point, New York, Reformulation Study" being conducted by the U.S. Army Engineer District, New York.

DATA

The analyses discussed herein were performed using High Water Line (HWL) shoreline position data that were either interpreted from aerial photography or surveyed using an All-Terrain-Vehicle (ATV) equipped with Global Positioning System (GPS) equipment. A total of 11 Fire Island HWL shoreline position data sets representing shoreline

conditions during eight different months of the year and spanning a period of nearly 18 years provided the input to the analyses conducted in this study. Four of the HWL data sets were interpreted from rectified aerial photography (December 1979, April 1983, March 1988, and April 1995). Leatherman and Allen (1985) compiled the December 1979 shoreline position data set from aerial photography as part of their geomorphic analysis of the south shore of Long Island. The April 1983, March 1988, and April 1995 HWL data sets were interpreted from digitally rectified aerial photography by the Coastal and Hydraulics Laboratory at WES as part of the FIMP Coastal Processes studies. The remaining seven HWL shoreline position data sets were obtained using a kinematic GPS survey system mounted on an ATV and traversing the high water line between Fire Island Inlet and Moriches Inlet (Allen and LaBash 1996). These GPS survey data sets of the Fire Island HWL shoreline were provided by Dr. James R. Allen, U.S. Geological Survey, who also directed the survey program with partial funding provided by the Corps of Engineers, New York District. The GPS shoreline position surveys were conducted in: (1) August 1993, (2) September 1994, (3) August 1995, (4) November 1996, (5) January 1997, (6) May 1997, (7) September 1997. The original interpreted and surveyed HWL data sets were comprised of Northing and Easting coordinate pairs referenced horizontally to the North American Datum of 1983 (NAD83), in New York Long Island Zone 3104 State Plane coordinates, in units of meters. The HWL data sets were subsequently interpolated at 25-meter intervals relative to an arbitrary baseline oriented along the general trend of the Fire Island barrier. The result of this step was co-located shoreline position data sets (station and offset from baseline) that could be analyzed to determine for example, rates of shoreline change between various time intervals. The Fire Island baseline has a 71-degree azimuth orientation, is 50 km long, and its origin is centrally located in Fire Island Inlet.

ANALYSES

Shoreline Change

The influence shoreline undulations have on typical engineering calculations at Fire Island is readily illustrated by examining the rate of shoreline change over various time intervals. For example, the rates of shoreline change over a representative 10-km reach in central Fire Island (approximately from Fire Island Pines to Watch Hill) for the intervals December 1979 to April 1983, April 1983 to March 1988, and March 1988 to April 1995 are plotted in Fig. 2. Fig. 2 shows that the local rate of shoreline change can be relatively large, ranging from about "10 m/year over an approximate 3-year interval to around "5 m/year over a 7-year interval. As can be seen in the figure, the rate of shoreline change is highly variable both spatially and temporally with high rates of accretion followed by high rates of erosion at the same location depending on the interval of time examined. Because of this high degree of variability, the historical rate of shoreline change may be relatively small (on the order of 1 m/year erosion) but have a large standard deviation (on the order of 5 m/year). Fig. 3 illustrates the wide fluctuations in shoreline position that result in the large rates of shoreline change and high degree of spatial variability in the rates plotted in Fig. 2. Note the comparatively wide berm width present on the right-hand side of both images and the very eroded condition (narrow berm width) in the central portion of the top image that subsequently

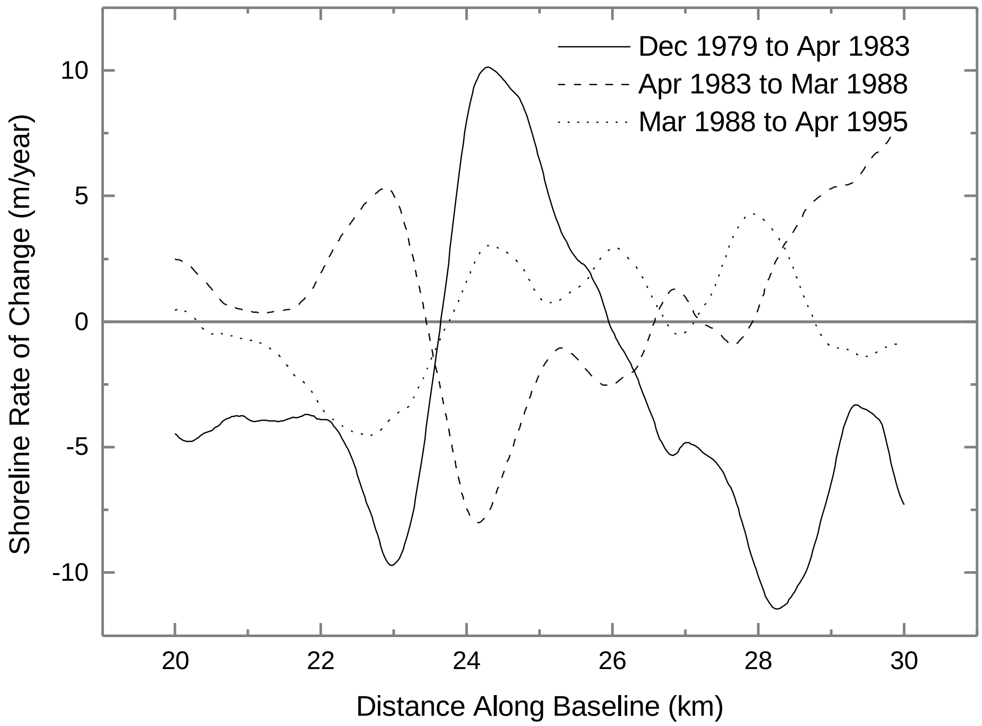

Fig. 2. Shoreline rate of change over a 10-km segment of Fire Island.

(a)

(b)

Fig. 3. Example of shoreline undulation (a) April 1983, (b) April 1995 (baseline stations 21.0 through 25.0 km).

evolved to a substantially wider berm condition in the bottom image. Table 1 lists computed rates of shoreline change since 1979 over the entire Fire Island barrier together with the standard deviation associated with the listed shoreline change rate. From Table 1 it is seen that on average, the Fire Island shoreline is retreating landward at rates ranging from 0.04 m/year to 2.5 m/year depending on the time interval. However, the large standard deviation (equal to or exceeding 2.5 times the mean rate of shoreline change) indicates that notable shoreline accretion occurred at some locations during each of the time intervals. The approximate 15-year (December 1979 to April 1995) average rate of shoreline change was calculated at –0.66 m/year. The rate of shoreline change plays a central role in the development of sediment budgets and estimating design quantities such as beach fill volumes and renourishment intervals. Because the large spatial and temporal variability in the shoreline rate of change is largely influenced by the presence of shoreline undulations, a detailed examination of these morphologic shoreline features was initiated. The goal of these analyses was to quantify the space and time scales associated with the shoreline undulations in order to develop design concepts compatible with the presence of shoreline undulations. Another goal was to develop a better understanding of the shoreline undulation scale of influence in the context of the larger-scale morphology and evolution of the Fire Island barrier.

Table 1. Average Shoreline Change Rates on Fire Island Since 1979

Time Interval	Rate of Shoreline Change (m/year) [1]	Standard Deviation (m/year)
1979 – 1983	–2.5	"6.7
1979 – 1988	–1.0	"2.5
1979 – 1995	–0.66	"1.9
1983 – 1988	–0.04	"5.2
1983 – 1995	–0.14	"2.9
1988 – 1995	–0.22	"3.6

[1] Adjusted to account for beach fill placement.

Spectral Analysis

This section discusses a spectral analysis of the shoreline position data aimed at quantifying the length scale of the shoreline undulations observed and measured on Fire Island (Fig. 4). An estimate of the power spectrum was computed for each of the shoreline position data sets using the Fast Fourier Transform (FFT) technique, which transforms the data (in this case) from the spatial domain to a cycles per meter (inverse of the wavelength) domain. Peaks in the energy spectrum define those shoreline undulation wavelengths that contain the most energy and consequently represent the dominate wavelengths present in the input data. The first step in this analysis involved developing a method to isolate and extract the shoreline undulations from the shoreline position data. This step is necessary in order to remove the large-scale curvature associated with the ocean shoreline of the Fire Island barrier. This procedure is analogous to removing the tidal signal from data recorded by a wave gauge prior to analyzing the data for wind wave information and is referred to as de-trending the signal. The procedure used to isolate the shoreline undulation signal from the shoreline position data sets involved computing a running average shoreline position using a 1.525-km averaging window and then subtracting the average shoreline from the original shoreline. An example of the procedure is illustrated in Fig. 5 for a 10-km segment located in

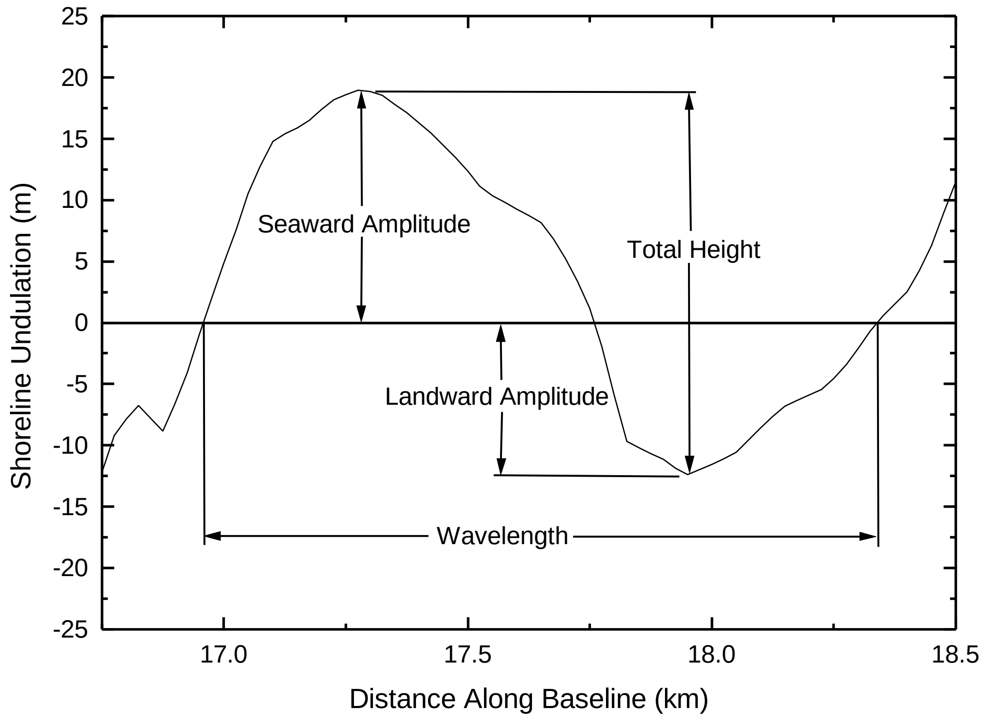

Fig. 4. Shoreline undulation wavelength and amplitude definition sketch.

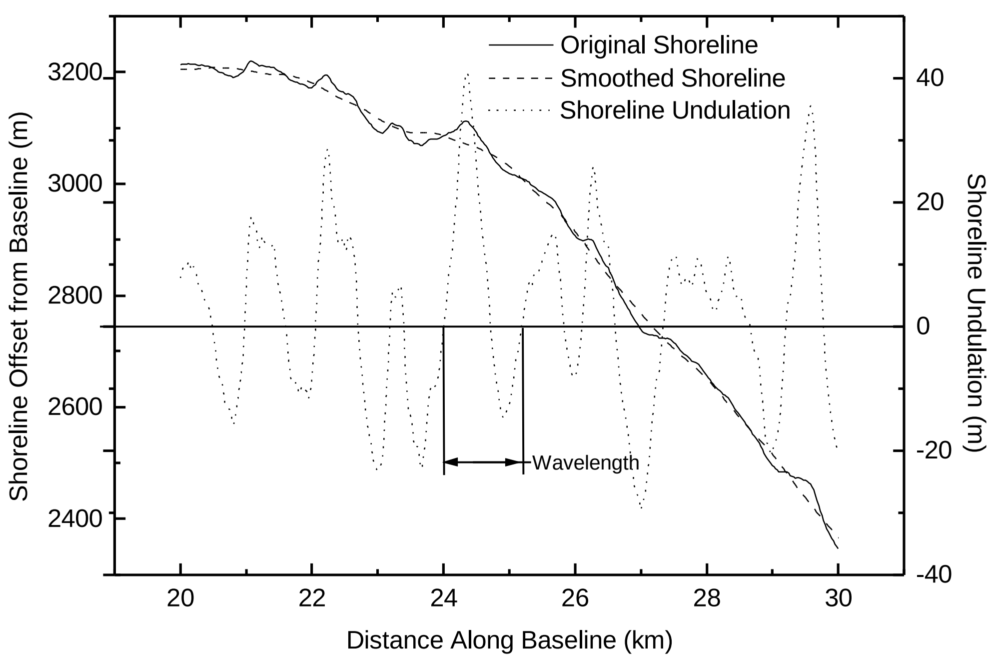

Fig. 5. Extraction of shoreline undulation signal.

central Fire Island using the April 1995 shoreline data set. After extracting the shoreline undulation signal from the shoreline position data, the next step involved processing the shoreline undulation data through the FFT analysis routine. The power spectrum estimates that resulted from the analysis were smoothed, and spectral peaks in the smoothed version of the power spectrum were used to identify the dominant shoreline undulation wavelengths. An example of the raw and smoothed power spectrum that resulted from the FFT analysis of the April 1995 shoreline undulation data set is provided in Fig. 6. Each of the shoreline undulation data sets were processed as described above and comparable results were obtained. Table 2 provides a summary of the results obtained from the spectral analysis. From Table 2 it is seen that in general only two spectral peaks were identified from the shoreline position data sets that were interpreted from aerial photography (only the March 1988 data set gave three spectral peaks). The corresponding shoreline undulation wavelengths were found to range from about 1 to 1.8 km. The data sets that were obtained by GPS survey methods resulted in the identification of not less than two and often more than three spectral peaks corresponding to shoreline undulation wavelengths in the 1 to 3-km range with most peaks concentrated in the 1 to 2-km wavelength range. The reason for the difference in the number of spectral peaks is unknown but believed to be a result of the different data capture methods used (photo interpretation versus on-the-ground survey). Of importance however, is that the statistically significant wavelengths of the shoreline undulations were found to be generally in the same range regardless of the data capture method. Based on the described spectral analysis it is concluded that the predominant wavelength associated with shoreline undulations on Fire Island ranges between about 1 and 2 km.

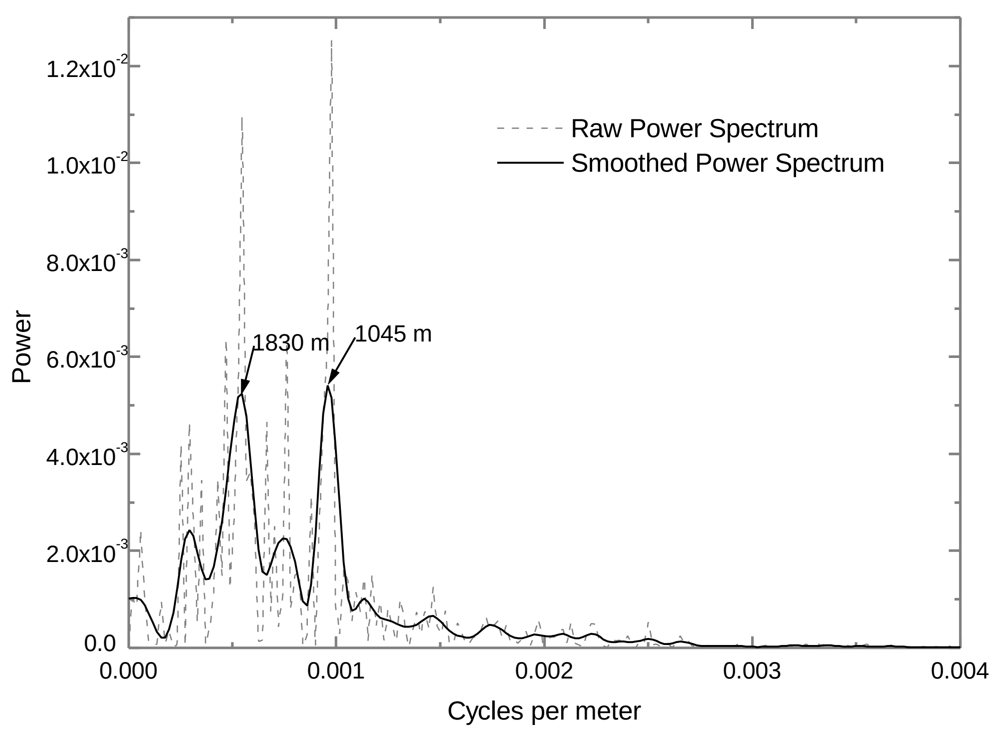

Fig. 6. Shoreline undulation power spectrum estimate (April 1995).

Table 2. Shoreline Undulation Wavelengths			
Date of survey/ photography	Shoreline Undulation Wavelength (m)		
	1st Peak	2nd Peak	3rd Peak
Photo Interpreted HWL Data			
December 1979	1090	1705	NA
April 1983	1705	1110	NA
March 1988	1350	1090	2560
April 1995	1045	1830	NA
GPS Survey Data			
August 1993	3010	1970	1220
September 1994	1045	1830	1465
August 1995	1045	1830	NA
November 1996	2050	1315	980
January 1997	2135	1315	1090
May 1997	1385	1090	NA
September 1997	1310	1065	NA

Individual Wave Analysis

This section discusses an analysis of individual undulations that was performed to obtain statistical estimates of the seaward and landward amplitudes as well as the total shoreline undulation "height" (Fig. 4). The seaward and landward shoreline undulation amplitudes become important in evaluating the impact anticipated shoreline undulations would have on typical beach fill design plans. The shoreline undulation data were processed using a zero up-crossing analysis routine that employed a minimum 5-meter seaward or landward amplitude threshold. That is, shoreline undulations with less than a 5-meter seaward or landward amplitude were considered in the noise range and did not enter in the statistical calculation of the shoreline undulation amplitudes. Root mean square (rms), significant (average of the largest third), and 1/10th (average of the largest tenth) amplitudes were computed for each data set. The results of the individual wave analysis are summarized in Table 3. The data in Table 3 indicate that the average rms

Table 3. Shoreline Undulation Amplitudes									
Date of survey/ photography	Shoreline Undulation Amplitudes (m)								
	total "height"			seaward			landward		
	rms	1/3	1/10	rms	1/3	1/10	rms	1/3	1/10
Photo Interpreted HWL Data									
December 1979	21	30	40	12	17	26	10	16	20
April 1983	34	48	59	19	28	38	18	27	41
March 1988	27	39	51	14	21	31	14	20	27
April 1995	35	49	60	20	29	39	18	25	32
GPS Survey Data									
August 1993	20	30	37	10	15	18	13	20	31
September 1994	18	25	31	10	14	17	10	14	19
August 1995	37	53	65	21	31	42	19	27	38
November 1996	26	36	45	14	20	26	15	21	34
January 1997	23	31	39	13	18	25	12	17	22
May 1997	20	27	31	11	15	20	11	15	22
September 1997	25	33	43	16	22	31	11	15	18
All Data									
Average	26	36	46	14	21	28	14	20	28
Standard Deviation	6	9	11	4	6	8	3	5	8

total shoreline undulation “height” on Fire Island is about 26 m with a standard deviation of about 6 m. The seaward and landward average rms amplitudes are both about 14 m. Significant amplitudes were found to be approximately 40 percent larger than the rms amplitudes and the highest one tenth amplitudes are nearly 100 percent larger than the rms amplitudes.

Spatial Analysis

This section describes an analysis aimed at identifying some of the spatial distribution and propagation characteristics of the shoreline undulations. The procedure involved comparing the shoreline undulation data to the computed landward and seaward rms amplitude and recording those baseline stations where the shoreline undulation exceeded either the landward or seaward rms amplitude. The results provide an indicator of the location of the seaward and landward bulges associated with the shoreline undulations. Consequently, if the shoreline undulations propagate along the shoreline one would expect to find both the landward and seaward rms amplitude exceeded at most baseline stations as the shoreline undulation moved as a unit along the shore. Likewise, if the shoreline undulations do not propagate, one would expect to find specific baseline stations where the landward rms amplitude is exceeded frequently and other baseline stations where the seaward rms amplitude is exceeded frequently.

Example results from the spatial analysis are illustrated in Figs. 7 and 8. Plotted in the top portion of the figures are the locations where the seaward rms amplitude was exceeded. Plotted in the bottom portion of the figures are the locations where the landward rms amplitude was exceeded. The individual shoreline undulation data sets are segregated from each other by distance from the horizontal line in the middle of the figure. The “trend line” plotted in Figs. 7 and 8 indicates the tendency for the presence of either the seaward bulge of a shoreline undulation (accretion cusp) or the landward bulge of a shoreline undulation (erosion cusp). The trend line was calculated by summing the number of times an accretion cusp was found at that station and subtracting the number times an erosion cusp was found at that station. Because each data set represents the shoreline condition at a specific instant in time, plotting all data sets in one figure (as in Figs. 7 and 8) provides an indication of the temporal characteristics of the shoreline undulations. For example, at baseline station 24.5 km in Fig 7, the shoreline undulation exceeded the seaward rms amplitude in 3 of the 11 data sets (May 1995, August 1993, and September 1994), the shoreline undulation did not exceed the seaward rms amplitude in any of the data sets, hence three tick marks are plotted in the top portion of the figure and the trend line is given a value of 3.

The 8-km-long shoreline coverage in Fig. 7 corresponds to the shoreline reach from Fire Island Pines to Davis Park (central Fire Island). In this figure there is notable segregation between the locations where the accretion and erosion cusps were found suggesting that the shoreline undulations do not propagate in the alongshore direction as a collective unit. Furthermore, the shoreline undulations seem to be present only intermittently, indicating that environmental conditions prior to or during the survey or photography may be important for the formation and prominence of the shoreline undulations. The interpretation of Fig 7 is that accretion cusps can be anticipated in two

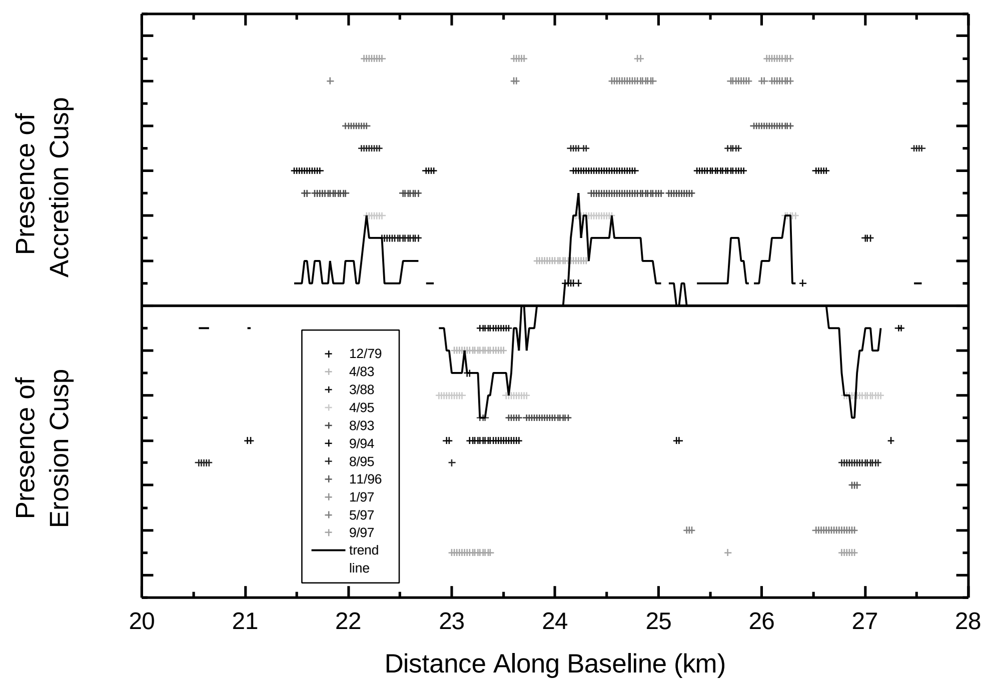

Fig. 7. Spatial analysis results: Fire Island Pines to Davis Park.

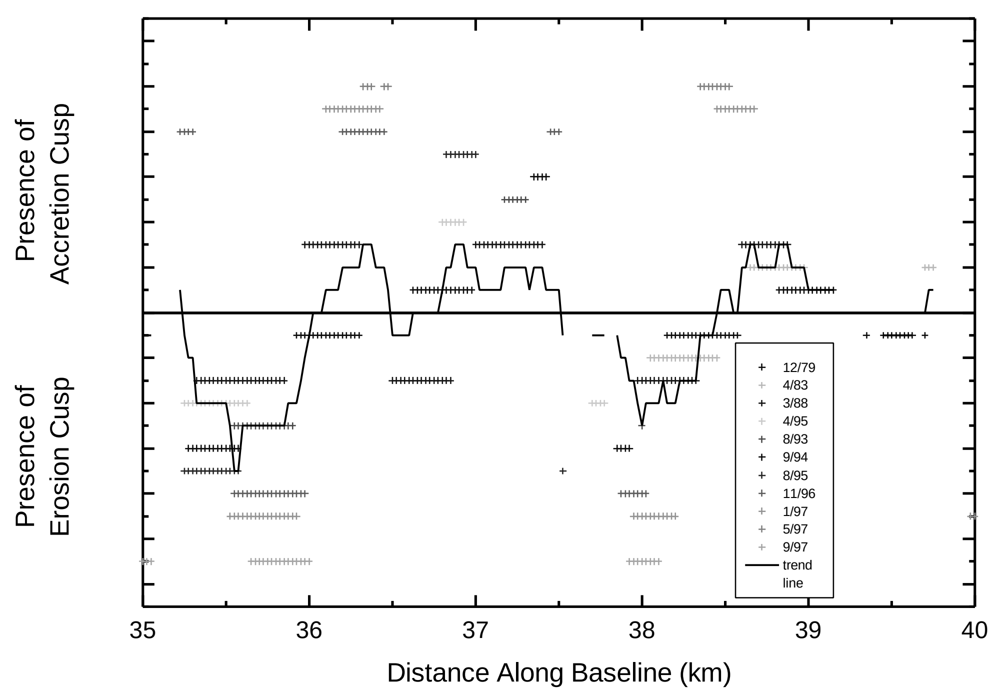

Fig. 8. Spatial analysis results: Old Inlet to Smith Point County Park.

locations from baseline station 21.5 km through 22.5 km and from baseline station 24.0 km through 26.5 km. Erosion cusps can also be anticipated in two locations from baseline station 23.0 km through 24.0 km and from baseline station 26.5 km through 27.5 km.

The 5-km-long shoreline coverage in Fig. 8 corresponds to the shoreline reach from Old Inlet to Smith Point County Park (about 12 km west of Moriches Inlet). The segregation between the locations where the accretion and erosion were found is reasonably apparent in Fig. 8, suggesting again that the shoreline undulations tend to be positioned in the same locations and do not propagate long distances as a collective unit. The interpretation of Fig. 8 is that erosion cusps can be anticipated to occur between baseline stations 35.0 km and 36.0 km and also between baseline stations 37.5 and 38.5 km. Accretion cusps can be expected between baseline stations 36.0 and 37.5 km and also between baseline stations 38.5 and 39.0 km.

Baseline locations or reaches where both the landward and seaward rms amplitudes are exceeded indicate propagation of the shoreline undulations within a limited domain, for example, in the vicinity of baseline stations 35.8 and 38.5 km in Fig. 8. Although this analysis does not definitively answer the propagation question, it does provide some insight into the spatial and temporal distribution of the shoreline undulations along the Fire Island shoreline. In summary, the results shown if Figs. 7 and 8 are representative of locations on Fire Island where shoreline undulations are frequently present and the trends are readily apparent.

DESIGN CONSIDERATIONS

Based on the analysis presented above, the influence of shoreline undulations on a typical beach erosion control design are discussed and potential design modifications are suggested to improve the compatibility of the design with the presence of shoreline undulations. Recent Federal beach fill projects in the northeastern U.S. have involved a protective dune fronted by design berm widths in the 30-m range with an additional 15-m wide advanced nourishment berm. The 15-m berm is constructed as a sacrificial feature intended to ensure that the protective design berm width is preserved throughout the renourishment interval (typically 3 to 6 years). The impact of the presence of shoreline undulations on these typical design dimensions is illlustrated in Fig. 9. The shoreline undulation signal developed from the April 1995 shoreline position data and plotted in Fig. 5 is superimposed on the post-construction shoreline in Fig. 9. As seen in the figure, the development of shoreline undulations on the post-construction shoreline will effectively reduce the sacrificial berm width that results from the placement of advanced nourishment material over significant portions of the project. Based on the data plotted in Fig. 9, the width of the advanced nourishment berm is less than half its intended width over 31 percent (3.1 km) of the project and the design berm is compromised over 13 percent (1.3 km) of the project. These conditions, which can be expected to occur either during construction or soon thereafter, will undoubtedly lead to shorter than designed renourishment intervals or a reduced level of protection because of encroachment into the design berm. It is acknowledged that the shoreline undulations

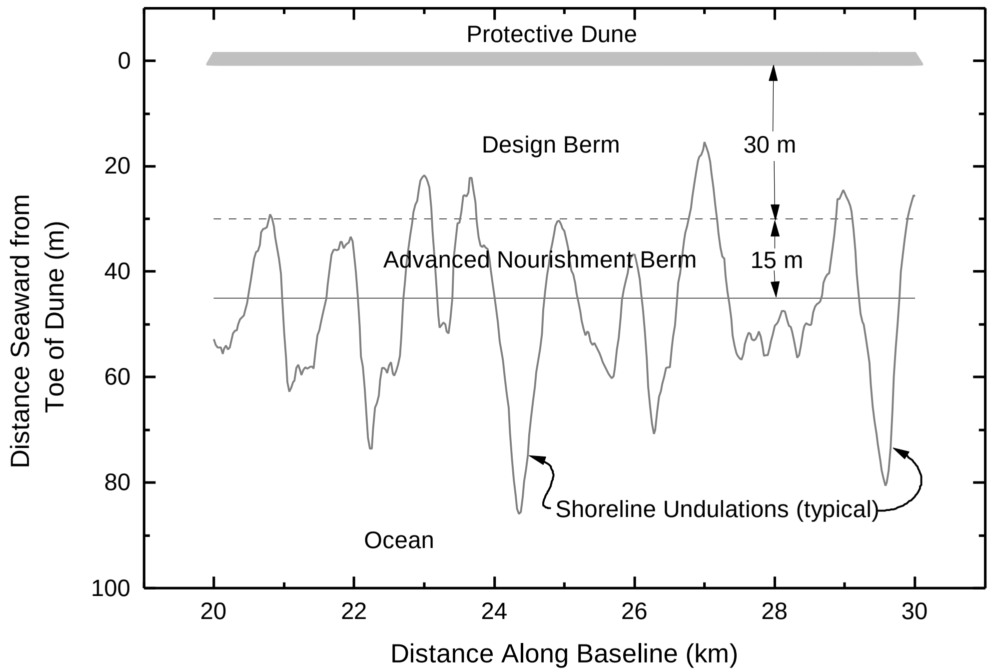

Fig. 9. Shoreline undulation impact on typical beach fill design.

plotted in Fig. 9 correspond to a specific shoreline reach at a specific historic point in time and may not be representative of all locations at all times. However, the previous analyses have quantified the landward rms amplitude of the shoreline undulations on Fire Island at about 14 m (Table 3) which is very close to the typical 15-m advanced nourishment berm width.

An improved design would involve reconsideration of the design goals and economic justification (project benefits) for the overall project. In the case of Fire Island, major project benefits result from the reduction of storm damages within the estuarine-margin communities along the northern shoreline of Great South Bay. In fact, these “off-site” benefits outweigh the benefits derived from the protection of properties on Fire Island. The project will provide storm damage protection to the upland properties by preventing breaching of the barrier island, which would lead to higher water levels in Great South Bay and associated flooding of the low-lying communities that border the bay. Therefore, a major design goal is to prevent breaching of Fire Island. Another design goal is to reduce storm-induced damages to structures and properties on Fire Island. Both of these design goals can be achieved through the construction of a dune and a wide protective berm. However, as illustrated in Fig. 9, the occurrence of shoreline undulations will tend to locally degrade the effectiveness of the typical design.

One approach to designing for the presence of shoreline undulation would be to construct an even wider beach berm (a “shoreline undulation buffer” zone) upon which shoreline undulations could form without compromising the design berm width or significantly impacting the advanced nourishment berm. This approach however, would

require adding approximately 15 m to the berm width and is expected to significantly increase the cost of the project because of the large volume of sand needed to construct the wider beach berm. A design concept that relies more on the dune structure and less on a wide berm to provide the desired level of protection may prove to be an effective and cost efficient alternative to the traditional design on Fire Island. It is noted however, that the dune must be protected from erosion through the construction of a berm with sufficient width to allow for the occurrence of shoreline undulations and the expected long-term shoreline recession between renourishment intervals.

CONCLUDING DISCUSSION

Shoreline undulations are a natural part of the Fire Island shoreline morphology and the presence of shoreline undulations should be anticipated after the construction of any beach erosion control project on Fire Island. The analyses discussed herein have shown that the wavelength of the shoreline undulations generally ranges between 1 and 2 km. The total rms shoreline undulation height was determined to be about 26 m. The landward and seaward rms amplitudes were both quantified at about 14 m. A spatial analysis indicated that the shoreline undulations on Fire Island do not appear to propagate from one end of the barrier to the other. Propagation of the shoreline undulations with in a limited (1 to 2 km) domain is possible. An important finding of the spatial analysis was that the seaward and landward bulges of the shoreline undulations were preferentially positioned along the shoreline. That is, based on the data sets examined in this study, certain locations along the shoreline can be expected to periodically develop large erosion or accretion cusps but not likely both. This finding indicates that the shoreline undulations may be excited by specific environmental forcing conditions (waves from a particular direction) and their location controlled by irregularities in the offshore bathymetry. In support of the assertion that specific environmental forcing excites the shoreline undulations is the finding from the spatial analysis that the shoreline undulations are intermittent features that are more prominent in some data sets than in others. Further study is required to determine the validity of this speculation.

The impact of shoreline undulations on a typical beach fill design configuration was shown to be significant and could lead to greater than anticipated maintenance costs or a reduced level of protection. Explicit consideration of the presence of shoreline undulations in the development of alternative design configurations was found to be essential for a successful project. Alternative design concepts include construction of a “shoreline undulation buffer” or constructing a substantial dune section that provides the desired storm protection without relying on a wide beach berm for protection. Regardless of how the design is modified, the geometric characteristics of the shoreline undulations on Fire Island must enter into the development of the design concept for a successful project.

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